DESIGN CONSIDERATIONS FOR LARGE FORMAT FAR-INFRARED ARRAY DETECTORS

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ABSTRACT

Efficient long wavelength broadband and spectral imaging on SOFIA and in future FIR/sub-mm missions will require large two-dimensional detector arrays. While monolithic near infrared arrays of up to 2048 x 2048 pixels are available, observations at wavelengths beyond 40 µm are still limited to mosaics of 32 x 32 or less pixels. We describe how to combine state-of-the-art FIR/sub-mm photoconductor technology and the elaborate industrial production techniques of the near and mid-infrared to produce larger, more reliable and eventually easier to make long wavelength arrays. This approach includes monolithic photoconductor array configurations optimized for quantum effciency and dark current. For electrical connection to a two-dimensional readout chip indium bump bonds similar to those in shorter wavelengths large-format arrays are used. The readout is based on the successful cryo-CMOS technology developed for SIRTF and SOFIA/AIRES. Differences in thermal contraction between detector and readout materials are addressed using techniques developed for large HgCdTe arrays. Initially, we plan for extrinsic Germanium photoconductor arrays of up to 128 x 128 pixels for wavelengths out to 130 µm. Longer wavelengths can be covered as blocked-impurity band Germanium, GaAs or other new detectors become available. Larger arrays may become feasible once the design concepts have been proven.

INTRODUCTION

Wanted: 128 x 128 or larger far-infrared arrays

Efficient long wavelength broadband and spectral imaging in future far-infrared (FIR) and sub-millimeter missions will require large two-dimensional detector arrays. For example, to fully sample the 8 arcmin field-of-view of the SOFIA telescope (2 pixels per λ/D, D = 2.5 m) arrays of 128 x 128 pixels at 100 µm and 64 x 64 pixels at 200 µm will be needed. Other FIR telescopes and modifications of SOFIA, e.g. a wide field camera at the location of the tertiary mirror, or FIR integral field spectrometers will require even larger arrays.

Present status: 5 X 5 … 32 X 32 far-infrared mosaics

Until the early 1980's FIR detectors have been limited to single pixels. Then for the first infrared satellites, small manually assembled mosaics of individual photoconductor crystals have been developed:

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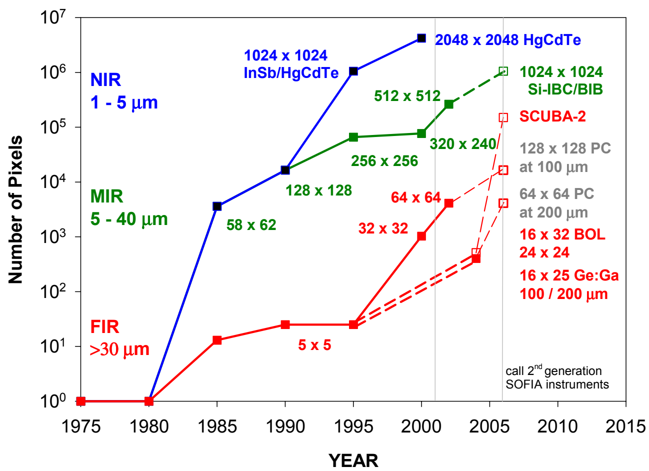
63 photoconductors on IRAS, and 3 x 3 elements of Ge:Ga (40 to 110 µm) and 2 x 2 elements of stressed Ge:Ga (120 to 220 µm) on ISO. Onboard the Kuiper Airborne Observatory (KAO) instruments were using a 5 x 5 array of stressed and unstressed Ge:Ga and arrays of up to 60 bolometers. More recently, a 32 x 32 pixel camera of Ge:Ga photoconductors has been developed for SIRTF, scheduled for launch in 2003. An extension of this design to 64 x 64 pixels is under development for potential future use on SOFIA. Other ongoing FIR array developments are part of SOFIA instrument projects: 16 x 25 unstressed and stressed Ge:Ga arrays, and bolometer arrays of 16 x 32 and 24 x 24 elements. For ground based observations the SCUBA-2 project aims for bolometer arrays of several 10^5 pixels in 2005 or later.



Megapixel cameras in the near- and mid-infrared

While FIR astronomers are still struggeling to push the number of pixels in their arrays beyond the 10^3 mark, array detectors for near-infrared (NIR) and mid-infrared (MIR) astronomical observations have grown to impressive sizes of up to 2048 x 2048 pixels.

Figure 1
The development of infrared array sizes in different wavelength ranges.

Development funding: Big difference between NIR/MIR and FIR/SUB-millimeter

Although considerable effort and resources were invested by the astronomical community to optimize NIR and MIR arrays for their specific needs, e.g. with regard to dark current, read noise and wavelength coverage, these developments have greatly benefited and leveraged off commercial and defense funded technologies. As the earth's atmosphere is completely opaque at FIR and Sub-mm wavelengths between 40 and 350 µm, there is essentially no commercial or defense interest in detectors for that wavelength range. FIR astronomers have therefore been facing the challenge to develop their own detector technology on research type funding levels.

Array Architecture and Manufacturing

Making large format NIR and MIR arrays uses only three key components and technologies which are to a large extent automated by industrial machinery:

1. Monolithic, two dimensional detector wafers with high optical fill factors, approaching 100%.
2. Integrated electronics chips with a two dimensional matrix of input gates, capable of integrating and multiplexing the detector signals at cryogenic temperatures (cryogenic readout electronics).
3. Interconnection technology, namely indium bump bonds, to 'sandwich' the detector wafer to the readout chip (direct hybrid).

FIR photoconductor and bolometer arrays require a much larger number of components and interconnections. Their assembly is to a large extent manual:

1. Individual detector pixels in integrating cavities to enhance their FIR photon absorption.
2. Foreoptics of either light cones or field lenses to enhance the optical fill factor.
3. Preamplifiers assembled of individual components, some of which need to be heated to keep operational in the cryogenic environment. Thermal decoupling from the colder detectors and shielding of thermally emitted straylight are required. For photoconductors, integrated cryogenic readout chips for a small number of detector channels (64) have been developed.
4. Many electrical interconnections and feedthroughs that are wire bonded or glued.

PROPOSAL

Combining the expertise of making direct hybrids of NIR and MIR detector arrays with state-of-the-art FIR detector materials can lead to direct hybrid FIR arrays of large formats. These would consist of less individual components and would be manufactured using automated processes. Therefore, they will eventually be easier to make and be more reliable.

Why photoconductors

For system aspects of an FIR instrument, photoconductors offer some distinct advantages:

1. They operate at temperatures between 1.5 and 3 K and therefore don't require sophisticated cooling machines for the mK-range.
2. They cover a wider dynamic signal range compared to bolometers and are less vulnerable to microphonics and pick-up noise.
3. Their requirements for electrical stability and readnoise of the associated readout electronics can be satisfied by available cryogenic CMOS technology.

We therefore propose to develop prototype direct hybrid arrays based on state-of-the-art doped Germanium photoconductors, i.e., Ge:Ga and/or Ge:Sb, and a two-dimensional version of an already proven FIR readout electronics.

Sensitivity

The sensitivity of these arrays will likely be comparable to today's best individual photoconductors, especially if the advantage of instantaneous phase space coverage with many pixels is considered. As more advanced FIR detector materials and structures become available, e.g. Germanium blocked-impurity band (BIB) detectors or GaAs, improvements of sensitivity (quantum efficiency) and other array properties like extended wavelength coverage, better uniformity and reduced crosstalk can be expected. FIR direct hybrid arrays may then play a similarly important role in astronomy as their shorter wavelengths cousins do now.

Detector arrays

Ge:Ga and Ge:Sb photoconductor materials have been developed at Lawrence Berkeley National Laboratory and have been used very successfully in FIR astronomy (KAO, ISO, SIRTF). Pixel geometries have been studied that will allow for monolithic two-dimensional arrays. A 1 x 1 x 2 mm^3 Ge:Ga crystal with FIR radiation entering on the 1 x 1 mm^2 surface through a transparent contact, delivered a detective quantum efficiency of 7.7% and a responsivity of 5.2 $A \cdot W^{-1}$. This performance is comparable to the best detectors placed in integrating cavities[1,2]. The contact opposite to the light entrance of that pixel has been fully metallized, doubling the FIR absorption depth of the crystal by reflection and enabling electrical contact to a readout electronics.

Based on these encouraging results an 8 x 8 element monolithic array has been manufactured using a single Ge:Ga block, 2 mm thick and 8 x 8 mm in square dimension. A transparent contact is implanted on one surface for FIR radiation entrance and the back surface is heavily doped and metallized, following the experience gained with the single test pixel. Saw grooves on the back of the crystal, 150 μm wide and 1.8 mm deep, define a matrix of 8 x 8 pixels. This separation between pixels is expected to provide almost complete optical and electrical isolation between pixels.

We consider this configuration to be ideal for producing and testing prototype direct hybrids. Future modifications might comprise a reduction of the optical pixel size to fit more pixels into a given physical area, and optimization of the transparent contact for maximum transmission.

Cryogenic readout electronics

Integrated cryogenic CMOS readout electronics for FIR Ge:Ga detectors have successfully been developed and used in ISO's photometer and in the 32 x 32 camera of the MPIS instrument on SIRTF. These circuits contain 32 input channels consisting of capacitive feedback transimpedance amplifiers (CTIA). Recently, these circuits have been modified with an AC-coupled input for improved bias uniformity of the attached detector array and selectable feedback capacitors to adapt the well capacity to variable photon fluxes, e.g.

high resolution spectroscopy or broadband imaging on SOFIA. These 32-channel circuits can be used for testing prototype two-dimensional FIR detector arrays.
For direct hybrid arrays the readout circuit's geometry will have to be redesigned to form a two-dimensional matrix of input gates that matches the pixel pitch of the detector array. Other design parameters and circuit characteristics are expected to remain unchanged, as they are already optimized for the operation of FIR detectors.

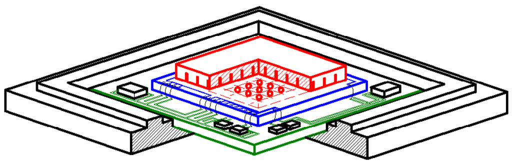


Figure 2
Schematic of a direct hybrid FIR detector array
Light enters the detector chip from top through a transparent contact. On its backside saw grooves define individual pixels. Electrical contact to the readout chip is made through Indium ball bonds. The detector/readout sandwich is mounted on a custom ceramics board along with auxiliary capacitors and resistors.

Interconnection and thermal control

For a direct hybrid of a two-dimensional Ge:Ga detector array and a readout chip, indium bump bonds similar to those in shorter wavelengths large-format arrays will be used. The larger detector spacing on FIR detector arrays allows larger indium bumps making the hybridization process easier.

The major challenge in the design of the Ge:Ga hybrid is allowing for the difference in thermal contraction between detector and readout. As the hybrid assembly cools to its operating temperature, the detector and readout contract by different amounts, causing the indium bumps connecting the two materials to stretch and eventually, after several thermal cycles, to break. The problem is similar to that of HgCdTe detectors hybridized to silicon readouts where detector manufacturers have devised methods of constraining the readout to contract like the detector material. The simpliest method is to bond the readout to a strong, rigid material that contracts like the detector. Since Germanium contracts five times more than Silicon between room temperature and 2K, the Silicon must be forced to contract more than it would if it were unconstrained. This technique has been demonstrated with HdCdTe detector arrays up to 27 mm on a side. Since the thermal contraction of Germanium is approximately the same as HgCdTe (about 0.1%), Ge:Ga arrays of similar dimensions are feasible with existing technology.

Detector cooling and straylight control

FIR detectors typically operate at temperatures $\leq$ 3K. Due to the architecture of a direct hybrid the thermal coupling of the detector chip to the cooling bath is softer than desirable. We believe that sufficient cooling power can be provided through multiple contact wires to the top (bias) contact of the detector chip. Thermal modeling will be used to verify this assumption. At the same time the design and operation of the readout electronics will minimize its power dissipation to $\leq 1\mu$W per channel.

Experience with NIR and MIR direct hybrid arrays has shown, that certain transistors in a readout chip may show NIR light emission ("glow"), or if heated up through operational currents, could emit thermally. We will use thermal modeling and analysis of such effects to understand their mechanisms and to find counter measures. Metallization of areas of the readout chip may be used to shield the detectors from unwanted radiation and to distribute dissipated heat, so that all parts of the chip will remain below the temperature threshold for thermal emission in the detector's response band.

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